

Acoustoelectric Effect in degenerate Carbon Nanotube

K. A. Dompreh^{a,1,*}, N. G. Mensah^b, S. Y. Mensah^a, F. Sam^a, A.K. Twum^a

^a*Department of Physics, College of Agriculture and Natural Sciences, U.C.C, Ghana.*

^b*Department of Mathematics, College of Agriculture and Natural Sciences, U.C.C, Ghana*

Abstract

Acoustoelectric Effect AE in degenerate Carbon Nanotube (CNT) was theoretically studied for hypersound in the regime $ql \gg 1$. The dependence of acoustoelectric current j^{ac} on the acoustic wave number \vec{q} and frequency ω_q at $T = 10K$ and scattering angle ($\theta > 0$) was evaluated at various harmonics $n = \pm 1, 2, \dots$ (where n is an integer). In the first harmonics ($n = \pm 1$), the non-linear dependence of j^{ac} on ω_q and \vec{q} were obtained. For $n = \pm 2$, the numerically evaluated j^{ac} qualitatively agreed with an experimentally obtained result.

Keywords: Carbon Nanotube, Acoustoelectric, degenerate, hypersound

Introduction

Carbon Nanotubes (CNT) discovered by Iijima [1] are emerging as important materials for electronic applications due to their remarkable electrical and mechanical properties [2, 3, 4]. The metallic and semiconducting Single-Walled Carbon Nanotube (SWCNT) have been proposed as the most viable materials to develop high performance thin films to completely eliminate the

*Corresponding author
Email: kwadwo.dompreh@ucc.edu.gh

use of critical metals in electronic devices such as: i) Indium in transparent conducting films (*TCF*, indium oxide doped by tin, *ITO*) and ii) Indium and Gallium as semiconductor *InGaZnO* (*a* – *IGZO*) in thin film field effect transistors (*TFTs*) for applications in optoelectronics [5, 6, 7, 8, 9]. The unusual band structure [10, 11, 12] of *CNT*, coupled with large electron densities and high drift velocities (with electron mobility of $\mu \approx 10^5 cm^2/Vs$) at room temperatures opens a way for employing carrier control processes rather than direct electrical control [13]. In the linear regime, electron-phonon interactions in *CNT* at low temperatures leads to emission or absorption of large number of coherent acoustic phonons [14, 15, 16]. When the momentum of the acoustic phonons is absorbed by the conducting electrons, it leads to the appearance of *d.c* electric field [17, 18, 19, 20, 21]. This phenomena is known as Acoustoelectric effect *AE* [22, 23, 24, 25, 26]. Studies of Acoustoelectric effect in bulk materials such as Gallium Nitride (*GaN*) [27, 28, 29] with applications in *GaN* film bulk acoustic resonators (*FBARs*), Indium Antimonide [30] and *GaAs/LiNbO₃* [31] has being reported.

With the advent of low-dimensional materials, *AE* has been intensively studied in quantum wells [32] to produce quantized current in $1 - D$ channels [33] for light storage and to induce charge pumping in nanotube quantum dots [34]. *AE* studies in superlattices [35, 36], quantum wires [37, 38] and Zinc Oxide (*ZnO*) Nanowires [39] has been reported. Recently, the need for acoustically driven current flow in semiconductor nano- structures has received particular attention as a means of generating or controlling single electrons and photons for quantum information processing [40, 41, 42]. From the hypersound absorption [43] studies conducted on *CNT*, it was found that

CNT exhibit good AE effect but till date, there is no general analytical theory of Acoustoelectric effect in *CNT*. However, a few experimental work by Ebbecke et. al. [44] and Reulet et. al [45] in *CNT* has been carried out. In this paper the theoretical treatment of AE in *CNT* in the hypersound regime $ql \gg 1$ (where q is the acoustic wave number, l is the mean free path of an electron) is carried out. The general expression obtained is analysed numerically for harmonics $n = \pm 1, \pm 2$ (where n is an integer). The paper is organised as follows: In section 2, the kinetic theory based on the linear approximation for the phonon distribution function is setup, where, the rate of growth of the phonon distribution is deduced and the acoustoelectric current (j^{ac}) is obtained. In section 3, the final equation is analysed numerically in a graphical form at various harmonics. Lastly the conclusion is presented in section 4.

1. Theory

Proceeding from [22, 23], the Acoustoelectric current j^{ac} in the hypersound regime $ql \gg 1$ is given as

$$j = -\frac{4\pi\tau e}{(2\pi)^3} |C_q|^2 \int_0^\infty v_i [f(p+q) - f(p)] \delta(\varepsilon(p+q) - \varepsilon(p) - \hbar\omega) d^3p \quad (1)$$

where the velocity $v_i = v(p+q) - v(p)$, $f(\varepsilon(p))$ is the distribution function, p is the momentum of electrons and τ is the relaxation constant. The linear energy dispersion $\varepsilon(\vec{p})$ relation for the *CNT* is given as [46]

$$\varepsilon(\vec{p}) = \varepsilon_0 \pm \frac{\sqrt{3}}{2\hbar} \gamma_0 b (\vec{p} - \vec{p}_0) \quad (2)$$

The ε_0 is the electron energy in the Brillouin zone at momentum p_0 , b is the lattice constant, γ_0 is the tight binding overlap integral ($\gamma_0 = 2.54\text{eV}$).

The \pm sign indicates that in the vicinity of the tangent point, the bands exhibit mirror symmetry with respect to each point. After collision, $\vec{p}' = (\vec{p} + \hbar\vec{q})\cos(\theta)$ is the component directed along the CNT axis. Where θ is the scattering angle. At low temperature ($kT \ll 1$), the Fermi-Dirac equilibrium function is given as

$$f_{\vec{p}} = \exp(-\beta(\varepsilon_{\vec{p}} - \mu)) \quad (3)$$

with μ being the chemical potential, $\beta = 1/kT$, k is the Boltzmann constant. Inserting Eqn.(2 and 3) into Eqn.(1), and after some cumbersome calculations yield

$$j^{ac} = \frac{2e\pi|C_{\vec{q}}|^2}{\hbar} \exp(-\beta(\varepsilon_0 - \chi\vec{p}_0)) \{ \exp(-\beta\chi(\eta + \hbar\vec{q})\cos(\theta)) - \exp(-\beta\chi\eta) \} \quad (4)$$

where $\chi = \sqrt{3}\gamma_0 b/2\hbar$, and

$$\eta = \frac{-2\hbar^2\omega_{\vec{q}} + \gamma_0 b\sqrt{3}\hbar\vec{q}\cos(\theta)}{\gamma_0 b\sqrt{3}(\cos(\theta) - 1)}$$

For acoustic phonons, $|C_{\vec{q}}| = \sqrt{\Lambda^2\hbar\vec{q}/2\rho V_s}$. Where Λ is the deformation potential constant and ρ is the density of the material. Taking $\varepsilon_0 = \vec{p}_0 = 0$, the Eqn.(4) finally reduces to

$$j^{ac} = \frac{2e|\Lambda|^2\tau\hbar q^2\exp(-\beta\chi\eta)}{2\pi\hbar\omega_q} \left\{ \sum_{n=-\infty}^{\infty} \frac{\exp(-n(\theta + \beta\chi\eta))}{I_n(\beta\chi(\eta + \hbar\vec{q}))} - 1 \right\} \quad (5)$$

where $I_n(x)$ is the modified Bessel function.

Numerical analysis

The analytical solution of Eqn(5) is obtained numerically and the results presented graphically. The parameters used in the numerical evaluation are:

$|\Lambda| = 9\text{eV}$, $b = 1.42\text{nm}$, $q = 10^7 \text{ cm}^{-1}$, $\omega_q = 10^{12}\text{s}^{-1}$, $V_s = 4.7 \times 10^5 \text{ cm s}^{-1}$, $T = 10K$, and $\theta > 0$. The dependence of j^{ac} on the acoustic wave number (\vec{q}) and the frequency (ω_q) at various harmonics ($n = \pm 1, \pm 2$) are presented below. For $n = \pm 1$, the non-linear graph (with an initial curve) increases sharply to a maximum then decreases to a constant minimum value (see Figure 1a). By increasing the values of \vec{q} , the graph shift to the right with decreasing amplitude. In Figure 1b, it was observed that at $\omega_q = 0.6 \times 10^{12}\text{s}$, the j^{ac} increases to a maximum point and then falls to a minimum value. Increasing the values of ω_q , shift the graph to the right. More interesting is the nature of the acoustoelectric current j^{ac} . At $\omega_q = 0.6 \times 10^{12}\text{s}$, the ratio of the peaks balances on both side of the j^{ac} axis. At $\omega_q = 0.65 \times 10^{12}\text{s}$, the ratio of the j^{ac} peaks is more towards the negative side but a reverse occurs when $\omega_q = 0.7 \times 10^{12}\text{s}$. For $n = \pm 2$ (see Figure 2 (a and b)), the graph obtained for j^{ac} versus ω_q qualitatively agreed with an experimentally obtained results. In Figure 2b, it is also observed that the dependence of j^{ac} on q is strongly non-linear. The ratio of $\frac{j^{ac}}{\Gamma}$ (where Γ is the hypersound absorption) in the absence of a drift velocity V_D [43] is given as

$$\frac{j^{ac}}{\Gamma} = \frac{2e\tau\gamma_0 b\sqrt{3}}{\hbar}(\cos(\theta) - 1) \quad (6)$$

which is the Weinreich relation [21] and is dependent on the scattering angel θ . For better understanding of the obtained graphs, a 3D graph of j^{ac} versus ω_q and \vec{q} are presented. For $n = \pm 1$, the ratio of the height of the peaks in the positive side of j^{ac} far exceeded that in the negative side (see Figure 3a). In Figure 3b, for $n = \pm 2$, the graph showed peaks at certain intervals.

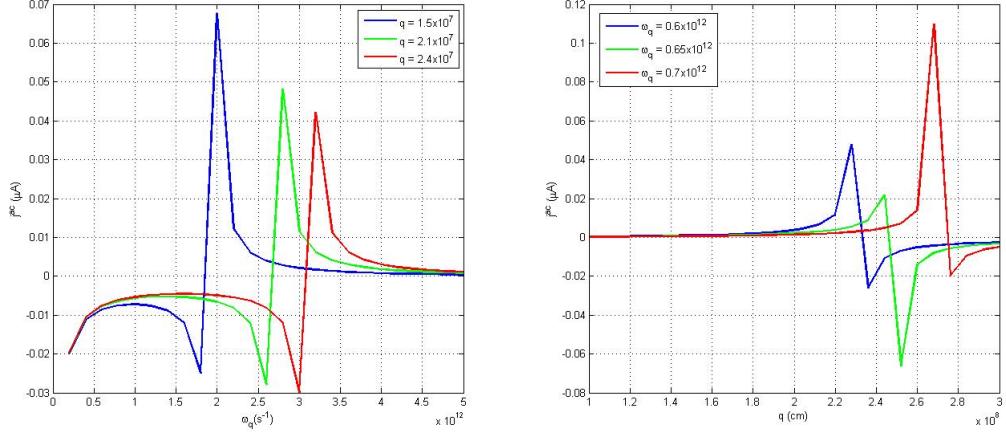


Figure 1: (a) Dependence of j^{ac} on ω_q at varying \vec{q} (b) Dependence of j^{ac} on \vec{q} for varying ω_q

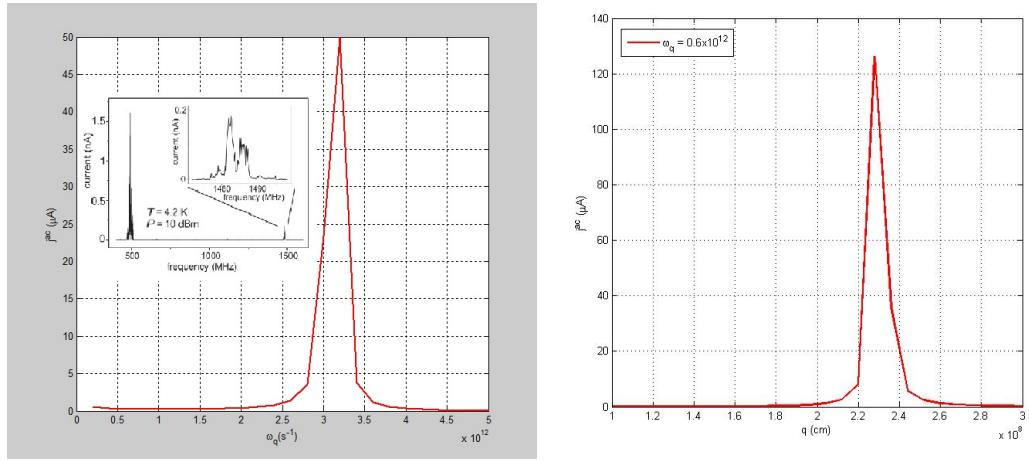


Figure 2: (a) Dependence of j^{ac} on ω_q at various \vec{q} insert shows the experimentally obtained acoustoelectric current [44] (b) Dependence of j^{ac} on \vec{q} for varying ω_q .

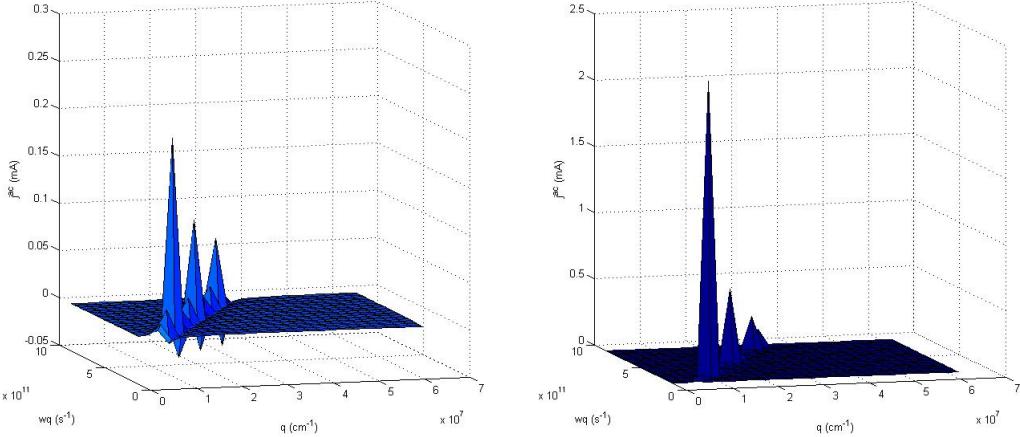


Figure 3: Dependence of j^{ac} on γ and \vec{q} at (a) the first harmonics $n = \pm 1$ (b) the second harmonics $n = \pm 2$

2. Conclusion

The Acoustoelectric Effect AE in a degenerate Carbon Nanotube CNT is studied for hypersound in the regime $ql \gg 1$. A strong nonlinear dependence of j^{ac} on the acoustic wavenumber \vec{q} and the frequency ω_q are observed. The dominant mechanism for such non-linear behaviour is the Acoustoelectric Effect which give rise to the acoustoelectric current j^{ac} . The analytically obtained acoustoelectric current j^{ac} qualitatively agrees with an experimentally obtained result.

Bibliography

- [1] Iijima, S., Nature 354, 56 (1991).
- [2] Odom, T.W., Huang, J.-L., Kim P. and Lieber, C.M. Nature 391, 62 (1998).

- [3] Bernholc, J.; Brenner, D.; Nardelli, M. B.; Meunier, V.; Roland, C. *Annu. Rev. Mater. Res.* 2002, 32, 347.
- [4] Ouyang, M., Huang, J.-L., C.L. Cheung and C.M. Lieber, One-Dimensional Energy Dispersion of Single-Walled Carbon Nanotubes by Resonant Electron Scattering ", *Science* 292, 702 (2001).
- [5] L. Hu, D. S. Hecht, and G. Gruner, *Nano Lett.* 4, 2513, 2004.
- [6] Z. C. Wu, Z. H. Chen, X. Du, J. M. Logan, J. Sippel, M. Nikolou, K. Kamaras, J. R. Reynolds, D. B. Tanner, A. F. Herbard, and A. G. Rinzler, *Science* 305, 1273, 2004.
- [7] M. Zhang, S. L. Fang, A. A. Zakhidov, S. B. Lee, A. E. Aliev, C. D. Williams, K. R. Atkinson, and R. H. Baughman, *Science* 309, 1215, 2005.
- [8] N. Sarah, K. Parikh, D. S. Suh, E. Munoz, H. Kolla, and S. K. Manohar, *J. Am. Chem. Soc.* 126, 4462, 2004.
- [9] M. Kaempgen, G. S. Duesberg, and S. Roth, *Appl. Surf. Sci.* 252, 425, 2005.
- [10] Dresselhaus, M. S., G. Dresselhaus, and A. Jorio. 'Unusual properties and structure of carbon nanotubes'. *Annu. Rev. Mater. Res.* 34 (2004): 247-278.
- [11] N. Hamada, S. Sawada, and A. Oshiyama, New one-dimensional conductorsGraphitic microtubules, *Phys. Rev. Lett.*, vol. 68, pp. 15791581, 1992.

- [12] R. Saito, M. Fujita, G. Dresselhaus, and M. S. Dresselhaus, Electronic structure of chiral graphene tubules, *Appl. Phys. Lett.*, vol. 60, pp. 22042206, 1992.
- [13] P. V. Santos, T. Schumann, M. H. Oliveira, Jr., J. M. J. Lopes, and H. Riechert, ‘Acousto-electric transport in epitaxial monolayer graphene on SiC’, *Applied physics letters* 102, 221907 (2013)
- [14] Avouris, Phaedon, Marcus Freitag, and Vasili Perebeinos. ”Carbon-nanotube photonics and optoelectronics.” *Nature photonics* 2.6 (2008): 341-350.
- [15] Hertel, Tobias, and Gunnar Moos. ”Electron-phonon interaction in single-wall carbon nanotubes: A time-domain study.” *Physical review letters* 84.21 (2000): 5002.
- [16] LeRoy, Brian J., et al. ”Electrical generation and absorption of phonons in carbon nanotubes.” *Nature* 432.7015 (2004): 371-374.
- [17] Galperin Yu M. and Kagan V. D., 1970 *Zh. Eksp. Teor. Fiz. (Soy. Phys.JETP)* 59 1657.
- [18] Abdelraheem S. K, Blyth D. P. and Balkan N., 2001 *Phys. Stat. Sol (a)* 185 2 247.
- [19] Sorbel R. . 1976 *Phys. Stat. Solidi B* 77 141.
- [20] Hutson A. R., McFee I. H. and White D. L., 1961 *Phys. Rev. Lett.* 7 273.

- [21] Weinreich G., 1956 Phys. Rev. 104 321.
- [22] Mensah, S. Y. and F. K. A. Allotey, 'AE effect in semiconductor SL', J. Phys: Condens.Matter., Vol. 6, 6783, (1994).
- [23] Mensah, S. Y. and F. K. A. Allotey, 'Nonlinear AE effect in semiconductor SL', J. Phys.: Condens. Matter. Vol. 12, 5225, (2000).
- [24] Busse, L. J., and J. G. Miller. 'Response characteristics of a finite aperture, phase insensitive ultrasonic receiver based upon the acoustoelectric effect'. The Journal of the Acoustical Society of America 70.5 (1981): 1370-1376.
- [25] Mason, Warren P. "Physical acoustics and the properties of solids." The Journal of the Acoustical Society of America 28.6 (1956): 1197-1206.
- [26] Spector, Harold N. "Interaction of acoustic waves and conduction electrons." Solid state physics 19 (1967): 291-361.
- [27] Weinreich, Gabriel, T. M. Sanders Jr, and Harry G. White. "Acoustoelectric effect in n-type germanium." Physical Review 114.1 (1959): 33.
- [28] Gokhale, Vikrant J., Yu Sui, and Mina Rais-Zadeh. "Novel uncooled detector based on gallium nitride micromechanical resonators." SPIE Defense, Security, and Sensing. International Society for Optics and Photonics, 2012.
- [29] S.Y. Mensah, N.G. Mensah, V.W. Elloh, G.K. Banini, F. Sam, F.K.A. Allotey, Propagation of ultrasonic waves in bulk gallium nitride (GaN)

semiconductor in the presence of high-frequency electric field, *Physica E: Low-dimensional Systems and Nanostructures* 28 (4), 500-506, 2005.

[30] Fleming, W. J., and J. E. Rowe. "Acoustoelectric effects in indium antimonide." *Journal of Applied Physics* 42.5 (1971): 2041-2047.

[31] Rotter, M., et al. "Giant acoustoelectric effect in GaAs/LiNbO₃ hybrids." *Applied physics letters* 73.15 (1998): 2128-2130.

[32] J. M. Shilton, V. I. Talyanskii, M. Pepper, D. A. Ritchie, J. E. F. Frost, C. J. B. Ford, C. G. Smith, and G. A. C. Jones, *J. Phys. Condens. Matter* 8, L531 (1996).

[33] C. Rocke, S. Zimmermann, A. Wixforth, J. P. Kotthaus, G. Bohm, and G. Weimann, *Phys. Rev. Lett.* 78, 4099 (1997).

[34] M. R. Buitelaar, V. Kashcheyevs, P. J. Leek, V. I. Talyanskii, C. G. Smith, D. Anderson, G. A. C. Jones, J. Wei, and D. H. Cobden, *Phys. Rev. Lett.* 101, 126803 (2008).

[35] S.Y. Mensah, F.K.A. Allotey, N.G. Mensah, H. Akrobotu, G. Nkrumah.'The influence of external electric field on acoustoelectric effect in a superlattice', *Superlattices and Microstructures* 37 (2), 87-97 2005.

[36] Mensah, S. Y., et al. "The influence of external electric field on acoustoelectric effect in a superlattice." *Superlattices and Microstructures* 37.2 (2005): 87-97.

- [37] Cunningham, J., et al. "Acoustoelectric current in submicron-separated quantum wires." *Applied Physics Letters* 86.15 (2005): 2105.
- [38] Bau, N. Q. and Hieu, N. V., "The Influence of the Electromagnetic Wave on the Quantum Acustomagnetoelectric Field in a Quantum Well with a Parabolic Potential", *PIERS Proceedings*, Guangzhou, China, Aug. 25-28, 2014.
- [39] Wang, Wei-Shan, et al. "A ZnO nanorod-based SAW oscillator system for ultraviolet detection." *Nanotechnology* 20.13 (2009): 135503.
- [40] O. D. D. Couto, Jr., S. Lazic, F. Iikawa, J. A. H. Stotz, U. Jahn, R. Hey, and P. V. Santos, *Nat. Photonics* 3, 645 (2009).
- [41] S. Hermelin, S. Takada, M. Yamamoto, S. Tarucha, A. D. Wieck, L. Saminadayar, C. Bauerle, and T. Meunier, *Nature* 477, 435 (2011).
- [42] A. Hernandez-Minguez, M. Mouller, S. Breuer, C. Pfuuller, C. Somaschini, S. Lazic, O. Brandt, A. Garcia-Cristobal, M. M. de Lima, Jr., A. Cantarero, L. Geelhaar, H. Riechert, and P. V. Santos, *Nano Lett.* 12, 252 (2012).
- [43] Dompreh, K. A., et al. "Hypersound Absorption of Acoustic Phonons in a degenerate Carbon Nanotube." *arXiv preprint arXiv:1502.07636* (2015).
- [44] Ebbecke, J., Strobl, C. J., and Wixforth, A., "Acoustoelectric current transport through single-walled carbon nanotubes", *Physical Review B*, APS, 2004.

[45] Reulet, B., Kasumov, Yu. A. , Kociak, M., Deblock, R., Khodos, I. I., Gorbatov, Yu. B. , Volkov, V. T. , C. Journet and H. Bouchiat 'Acoustoelectric Effect in Carbon Nanotubes', physical Review letters, Vol. 85 Number 12, 25, 2000.

[46] Mavrinskiy, A. V., and E. M. Baitinger. "Thermoelectric power in carbon nanotubes." Semiconductors 43.4 (2009): 480-484.